On two cryogenic systems of high purity germanium detector*

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July 8, 2013

Abstract Two cryogenic systems of high purity germanium detector, liquid nitrogen and mechanical coolers, are expound, together with explanations of merits and demerits for each kind of cooling methods. The resolutions of detector to the characteristic lines of ^{152}Eu under different cooling conditions are studied. The laboratory results indicate that the mechanical cooler (X-Cooler II) is an ideal replacement candidate for the liquid nitrogen cooler that is being utilized by BEMS at BEPC-II.

Key words beam energy measurement, liquid nitrogen, X-Cooler II

PACS ?????

1 Introduction

The upgraded Beijing electron-positron collider (BEPC-II) is a τ-charm factory with a center mass of energy range from 2.0 to 4.6 GeV and a design peak luminosity of 10^{33} $cm^{-2}s^{-1}$ [1, 2]. The upgraded Beijing spectrometer detector (BES-III) with high efficiency and good resolution both for charged and neutral particles was constructed and started data taking in 2008 [3]. The BES-III research region covers charm physics, charmonium physics, spectroscopy of light hadrons and τ-lepton physics [4].

After vast amounts of data are acquired and analyzed, in physics analyses, the statistical uncertainty becomes smaller and smaller, the systematic uncertainty plays an more and more prominent role [5, 6, 7], one of which is the uncertainty due to beam energy. To decrease the uncertainty of beam energy, a high accuracy beam energy measurement system (BEMS) [8, **?**, 10, 11] has been constructed at the north crossing point (NCP) of

*Supported by National Natural Science Foundation of China (10491303, 10775142) and 100 Talents Program of CAS (U-25).

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the BEPC-II, which is of great importance for many physics analyses at BES-III, such as τ mass measurement, charmonium resonance scans, and determination of the branching ratio with the uncertainty at the level of 1% to 2%. The working principle of BEMS can be recapitulated as follows [12]: firstly, the laser source provides the laser beam and the optics system focuses the laser beam and guides it to make head-on collisions with the electron (or positron) beam in the vacuum pipe, after that the backscattering high energy photon will be detected by the High Purity Germanium (HPGe) detector, which is the key instrument of BEMS. The accuracy of beam energy depends solely on the detection results of HPGe detector.

The crucial condition for HPGe detector functioning properly is the low temperature [13, 17, 18] that allows the single crystalline germanium structure of the detector to operate as a diode, which produces current proportional to the energy deposited by a gamma ray interacting with that structure. Two approaches are usually employed to get the temperature below 100 kelvins (K) : liquid nitrogen (LN_2) and mechanical coolers. The former is adopted for cooling the HPGe detector at BEMS. However, one conspicuous drawback to the use of LN_2 owes to the time required to fill the dewar. The experience at BEPC-II is the half-hour filling once a week for HPGe detector of BEMS. During the perfect data taking process of BES-III, the precious time has to be consumed for LN_2 filling.

Mechanical cooler is an ideal replacement for LN_2 because they can provide continuous cooling as long as electricity is available. Only concern here is the resolution of HPGe detector with mechanical cooler, since the range of cooling temperature for mechanical cooler is from 85 to 105 K that is a little bit higher than that for LN_2 (the boiling temperature for LN_2 is 77 K at standard temperature and pressure). Therefore, in this monograph besides the detailed description of two cryogenic systems, the resolutions with distinctive cooling methods are measured with the radiation source of ^{152} Eu. The laboratory results confirm the replacement advantage of the mechanical cooler over LN_2 cooler, which is being used at BEPC-II.

2 Two cryogenic systems

2.1 HPGe detector

Germanium detectors are semiconductor diodes having a P-I-N structure in which the intrinsic region is sensitive to ionizing radiation, particularly X-rays and γ-rays. There are three types of reaction which happen in Germanium semiconductor, that is photoeffect, Compton scattering and pair production [14, 15] and the latter two processes dominate when the energy of injection photon is greater than 1 MeV. The germanium has a net

impurity level of around 10^{10} atoms/cm^3, so that with moderate reverse bias voltage, the intrinsic region that is the entire volume between the electrodes is depleted, and an electric field extends across this active region. When photons interact with the material within the depleted volume of a detector, charge carriers (holes and electrons) are produced and are swept by the electric field to the P and N electrodes. This charge, which is in proportion to the energy deposited in the detector by the incoming photon, is converted into a voltage pulse by an integral charge sensitive preamplifier. Subsequent amplification and pulse height analysis add the pulse to accumulated histogram which eventually becomes the characteristic spectrum of the source.

The net impurity level of 10^{10} atoms/cm^3 for germanium crystal is an extremely small relative net impurity concentration compared to 4×10^{22} Ge atoms/cm^3 [14]. Fabrication of such a high purity detector often resorts to ion-drift technique. The ions of alkali materials like lithium and sodium can be drifted into germanium crystal to produce useful detector. The lithium atoms are easily ionized and are mobile enough to drift at elevated temperatures under the influence of a strong electric field. This process is so-called "Lithium ion drifting" and Ge(Li) conveniently indicates lithium drifted Germanium. However, the lithium mobility in germanium is so great and remains high enough at room temperature, which leads to an undesirable redistribution of the lithium. Therefore, the lithium profile of Ge(Li) detector must always be preserved at LN_2 temperature.

There are two kinds of HPGe detectors, n-type and p-type. Since the later is utilized by BEMS at BEPCII, the similar coaxial p-type HPGe detector [21] manufactured by ORTEC is adopted, whose model is GEM-20180-P. It has diameter of 54.0 mm and length of 50.2 mm, the relative efficiency is 23%. The energy resolution for the 1.33 MeV line of ^{60}Co is 1.67 keV.

There are two types of capsule for the HPGe detector [22]: the streamline and the PopTop structure. In the streamline system, the germanium crystal, preamplifer and high voltage filter are packaged in the capsule, the capsule and the cryostat share the same vacuum, the detector capsule is not demountable. For the PopTop system, the capsule has its own vacuum, it can be mounted on any of the available cryostats. It is convenient of the PopTop structure of HPGe detector to change the cooling method. The cryostat/dewar combinations can be cooled by LN_2, or the detector can be cooled using X-Cooler II, by cold head of cooler coupling with PopTop capsule of detector. For the experiment that follows, the PopTop detector will be used.

2.2 Liquid nitrogen cooling

The germanium crystal is cooled down to the working temperature by connecting with the thermal transfer device, the cryostat and the extension rod that are dipped into the LN_2-full dewar, and the cold is conducted from the dewar to the germanium crystal.

To make the heat exchange more easier, the thermal transfer device is usually made of copper. Before insert the cryostat detector into a dewar, a white silicone rubber collar should be placed onto the dewar, so that a gas-tight seal is formed. The silicone rubber contains two stainless steel tubes, which are used for LN_2 filling and gas exhaust. During filling, liquid nitrogen enters through either tube, the other tube will exhaust the excess liquid when the dewar is full.

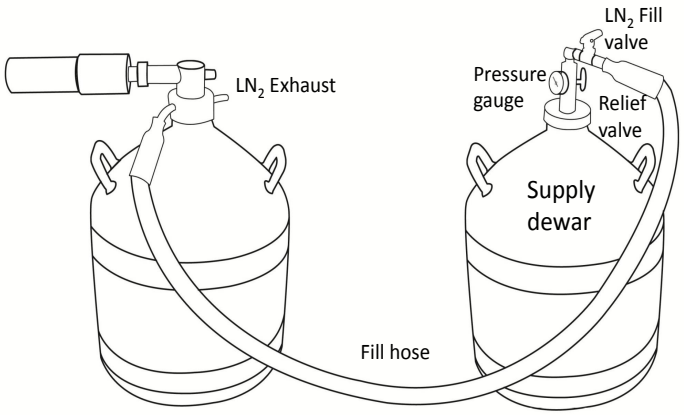


Figure 1: Tubing arrangement for liquid nitrogen transfer. The foam insulated fill hose is used to connect the supply dewar with the working dewar.

Preparing for filling the dewar by connecting the supply hose and an exhaust hose to the fill tubes in the silicone rubber collar. The exhaust hose is a six-foot length of plastic tubing which carries cold gas and liquid overflow way from the cryostat and electronics. The connection to the liquid nitrogen supply hose is made by a short length of plastic tube.

One common filling method use a standard 30-liter dewar of LN_2 as a supply dewar. As shown in Fig. 1, a gas-tight fixture, which holds a metal outlet tube and a gas inlet for pressurization, is attached to the supply dewar flange. The metal outlet tube is connected to a short length of plastic tube which serves as the supply hose. This tube carries liquid nitrogen out from dewar bottom. Transfer is effected by pressurizing the dewar at 3 to 5 psi with dry nitrogen gas[1]. The supply dewar or the gas inlet tube must have a pressure relief valve set at 5 psi. One must monitor the LN_2 filling continuously, once the dewar is

[1] "psi" is a kind of pressure unit, the relations of this unit with the others are as follows: 1 psi = 1 lbf $\cdot$ in^{-2} = 6895 Pa = 0.0689 bar = 0.068 atm or 1 atm = 1.013 bar = 1.013 $\times 10^5$ Pa = 14.7 lbf $\cdot$ in^{-2}.

full, the LN_2 overflow from the exhausting tube, the transfer process must be terminated immediately by turning off the filling switch. The transfer requires only a few minute if the gas pressure is not less than 5 psi. During the transfer process, frost is formed on the surface of the supply and exhaust hoses, allow them to thaw completely before removing them from the fill tubes [16].

The LN_2 supply system depicted above is called the self-pressurizing system, the pressure produced by the expansion of LN_2 to the nitrogen gas due to the evaporation of the LN_2. Therefore, about ten hours should be laid aside before the the pressure in dewar is high enough to press the LN_2 into the detector dewar quickly. But if the filling dewar stays without using for a long time, the LN_2 will evaporate slowly. Figure 2 shows the dependence of the loss of LN_2 on the storage time (the experiment temperature is 26° C). The longer is the storage time, the heavier of LN_2 loss. The time-loss dependence is almost linear as shown in Fig. 2.

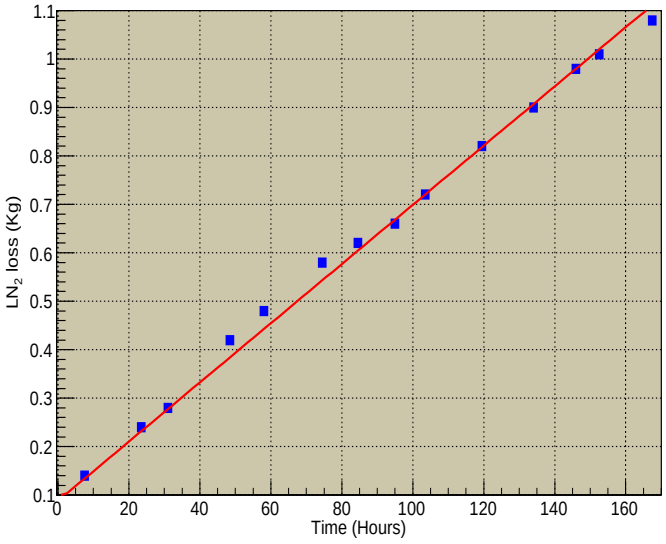


Figure 2: Dependence of the loss of LN_2 on the storage time. The points are experiment data while the line is the linear fit result.

Special attention must be paid for the cooling time, especially when the detector is firstly cooled down. It must be ensure that the boiling off of LN_2 will be excessive until the detector element is completely cooled. One cannot apply the high voltage to bias the detector before the germanium crystal is cooled for adequate long time. Concretely speaking, six hours is need for the detector used at BEMS. If the detector is cold enough, the bias will turn on. One can began data taken when the voltage is stable. It is worthy of stressing that accidental application of high voltage to a detector which in not fully cold can cause serious damage and even impair the detector thoroughly.

During the data taking period of BES-III, the BEMS is kept running simultaneously. The once-a-week filling schedule is followed to avoid unexpected warm-ups of HPGe detector. This reduces the probability that the high voltage bias is accidentally applied to the detector. However, such a regular filling schedule is unfavorable by both BES-III detector and BEPC-II accelerator. For the detector, some precious data taking time has to be consumed for refilling LN_2; for the accelerator, some time has to used to recover the preceding good running status. Moreover, when accelerator is under unstable status, accident may be happened and accelerator has to be stopped. These kinds of times is an opportunity for LN_2 filling. But as we mention before, the self-pressurizing technique need additional time for increasing the pressure from the evaporation of the LN_2. Therefore, the LN_2 have to be filled beforehand. However, the unpredictability of accident usually leaves the full dewar untouched more a week, which leads to lots of loss of LN_2 as indicated by the time-loss curve in Fig. 2.

Besides aforementioned disfavors, users of cooled detector have to face hazards associated with LN_2. For persons who transfer, store, and fill LN_2, they should avoid skin contact with LN_2, which causes frostbite. For the materials storing, transfering, and filling LN_2, most of which become brittle and fracture when exposed to the LN_2, especially the detector cryostat and electronics. In addition, transfer LN_2 should be operated in a well ventilated area, although the nitrogen gas is nontoxic, it is possible to cause asphyxiation by displacing air.

2.3 X-Cooler II cooling

Joule-Thompson cooler [23] is a kind of famous cooler. During cooling, compressed gases pass down a counter-current heat exchanger before being allowed to expand through a capillary or throttling valve. Cooling occurs upon expansion and the cool gas passes back up the heat exchanger, pre-cooling the incoming high-pressure gas. Kleemenko coolers are closely related to Joule-Thomson coolers. In the Kleemenko cycle it is not a gas that expands, but rather a mixture of gas and liquid. One or more liquid-vapor separators may be incorporated into the cycle so the expansion of the liquid can be used to pre-cool the vapor.

The Stirling cycle cooler is based on the Stirling cycle, which is invented and patented by Robert Stirling in 1816. In 1834 John Herschel proposed its use as a refrigerator in producing ice [24]. It was not until about 1861 that Alexander Kirk reduced the concept to practice [25]. Air was used as the working fluid in these early regenerative systems. Very little development of Stirling refrigerators occurred until 1946 when a Stirling engine at a Dutch company was run in reverse with a motor and was found to liquefy air on the cold tip [26]. The engine used helium as the working fluid, since earlier work at the company showed helium to give much improved performance to the engines. Stirling cryocoolers

have been used for about the last 60 years in cooling infrared sensors for tactical military applications in such equipments as tanks and airplanes.

The X-Cooler II solves both LN_2 and mechanical cooler problems. During cooling, the X-Cooler II uses patent technology [27] to remove residual oil and other contaminant, which allows the design to use standard, off-the-shelf compressors.

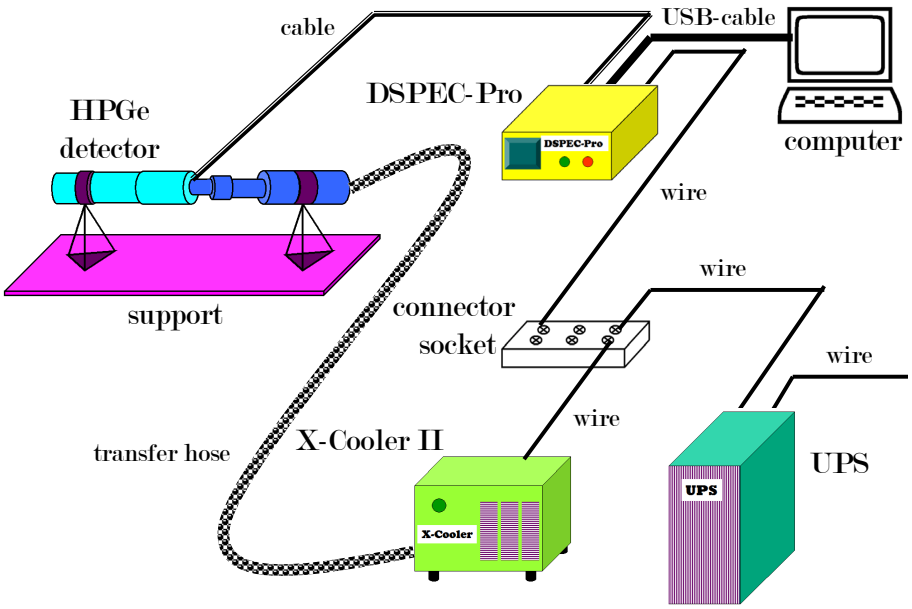


Figure 3: Design of Electronic cooler system for BEMS.

The X-Cooler II includes a compressor, transfer hose, heat exchanger, and cold head. All parts except for the heat exchanger are visible to user, refer to Fig. 3 for each part. The compressor is the box (denoted by the green box in Fig. 3) with a standard instrument plug on the rear for connecting AC power. In side the box is the compressor, a cooling fan, some AC wiring, and the plumbing of the refrigerant system. Attached to the rear panel of the compressor box is the transfer hose, which is made up of a stainless steel braid hose, 0.25 inch in diameter, that contains the gas pressure and return lines. Over the stainless steel braid hose is black insulting material and around that is a black plastic protective netting material. The transfer hose is often called "the umbilical cord" and connects the heat exchanger to the compressor box. At the end of transfer hose is the heat exchanger. It is a coiled set of copper and stainless tubing mounted inside the 3-inch diameter stainless tube. It is in this heat exchanger that the gas expansion for necessary cooling takes place.

The heat exchanger is inside the assembly known as the cold head. The cold head (connected with HPGe detector, and denoted by the dark blue tube in Fig. 3) also contains the thermal transfer devices and threaded coupling required to attach an ORTEC HPGe detector in a PopTop capsule to the X-Cooler II. Compared with LN_2 cooling, X-Cooler

II cooling is much simple. Pull out the detector from the dewar and warm the detector to the room temperature, remove the capsule from the cryostat and couple it to the cold head of X-Cooler II.

The length of time it takes the X-Cooler II to cool an HPGe detector to an acceptable temperature depends on the size of the detector and the ambient environmental conditions. For the coaxial p-type detector (GEM-20180-P) used at BEMS, the time between 12 and 14 hours[??] is enough to get to a table operating temperature and stabilize voltage for data taking of HPGe detector.

Comparing with LN_2 method, the accommodation of continuous cooling by the X-Cooler II resolves the interrupt annoy for data taking of BES-III, and the safety hazards associated with LN_2 is eliminated as well. Nevertheless, there are some hazards for the X-Cooler II to confront with, such as electrical hazard, temperature hazards and gas hazards, as to which user can find the details of precautions from user's manual [17].

As a matter of fact, a uninterruptible power system (UPS) is usually recommended to to be prepared for the electric cooler, which guarantees the power supply. If the X-Cooler II loses power, one can reapply power within 10 minutes of initial power loss. If the power loss lasts for more than 10 minutes, the system must be warmed to room temperature before re-cooling, the warmup time is 24 hours. Because the refrigerant is a mixture of gases which goes through a separation process when the compressor is running. If the compressor is shut off, warm up the cooler to room temperature will allow the refrigerant to equilibrium. If the cooler is started while the refrigerant is still separated, the compressor could be damaged because it is not operating the complete refrigerant mixture.

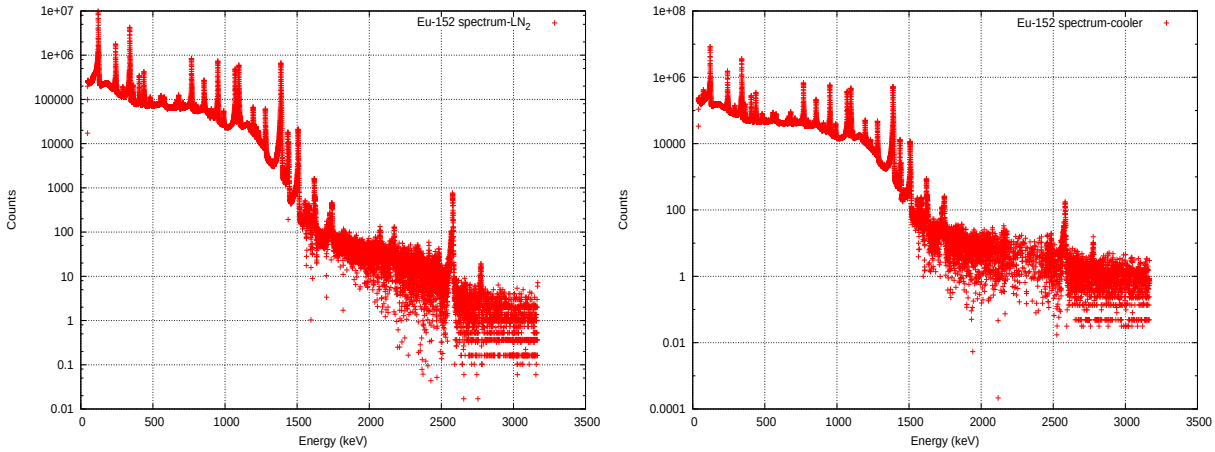
3 Resolutions of two cooling methods

By virtue of the working principle of BEMS [10, 12], the accuracy of beam energy is determined by that of the energy of backscattering energetic photon beam, which is measured by HPGe detector. If we want to replace LN_2 cooler by X-Cooler II, the detector resolution under electric cooling condition must be studied to ensure its capacity is compatible with that under LN_2 cooling condition. Therefore, this section focuses on the detector resolutions of two cooling methods.

3.1 Radiation source ^{152}Eu

The radiation source will be adopted is the nuclide ^{152} Eu whose decays is complicated, about 27% via β transitions, followed by photon emission, and 73% electron capture processes, with subsequent gamma emission. ^{152}Eu is an important gamma-emitter in radionuclide metrology and is used extensively to calibrate gamma-spectrometers for both

energy and efficiency. The gamma energy range emitted by ^{152}Eu is wide, the main lines is from hundred keV to 1.4 MeV [19, 20].



(a) LN_2 system (b) X-Cooler II system

Figure 4: The spectra of ^{152}Eu measured by HPGe detector under the cooling of liquid nitrogen (a) and X-Cooler II (b). The normalized background has been subtracted.

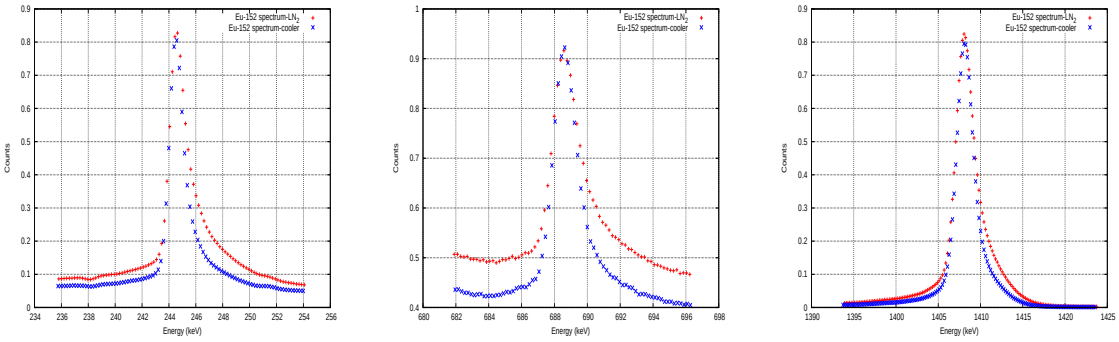
3.2 Setup and experiment

The HPGe detector can be classified into two subsystems: cooling system and data acquisition system. The later (refer to Fig. 3) is mainly composed of a DSPEC-pro and a computer. For our experiment, the Germanium crystal is connected with the ORTEC DSPEC-pro by detector interface module (DIM). The high voltage power supply, amplifier and multichannel analyzer (MCA) are integrated into DSPEC-pro. Then, the DSPEC-pro is plug into a computer by USB. All the control to the detector and parameters set are operated by computer.

A point like ^{152}Eu nuclide is used in this experiment, its characteristic peaks are recorded to monitor the change of HPGe detector resolutions under different cooling conditions. During the experiment, under the two cryogenic systems, the radiation source is placed along the cylindrical center axis of the Ge crystal, and about 1 cm far away from the top of the germanium detector. A foam plate with 1 cm thickness is sandwiched between the source and the detector. The whole resolution experiment is divided into two steps and before each step, both ^{137}Cs and ^{60}Co are used for the calibration of the HPGe detector.

The first step of experiment begins with the X-cooler II case, the data of measurement to radiation source are collected from 9:00 Nov. 21, 2012 to 16:50 Nov. 23, 2012. In order to remove the background effect, three days' background data are taken before and after the ^{152}Eu nuclide measurement, respectively.

The second step of experiment turns to LN_2 cooling method. The PopTop capsule of the detector is removed from the cold head of the X-cooler II, then connected with the cryostat, and put into a dewar filled with liquid nitrogen. After about six hours cooling, the germanium crystal is cold enough to apply the high voltage to bias the detector. The radiation source experiment is performed from 17:00 Dec. 7, 2012 to 8:00 Dec. 10, 2012. Also the background data of about two days are taken before and after the measurement of ^{152}Eu under the LN_2 cooling, respectively.



(a) line 244.7 keV (b) line 688.7 keV (c) line 1408.0 keV

Figure 5: The detailed shapes of characteristic lines of ^{152}Eu, from low to high energy region, namely, 244.7 keV, 688.7 keV, and 1408.0 keV.

3.3 Results

The spectra of ^{152}Eu measured by HPGe detector under two cryogenic systems are shown in Fig. 4, where removed are the backgrounds that have been normalized using the measurement time. The noise level for both LN_2 cooling and X-Cooler II cooling is the same, around 10 keV. Lots of characteristic peaks of ^{152}Eu from 122 keV to 1400 keV can be seen clearly, and three typical lines, that is the line 244.7, 688.7, and 1408.0 keV, can be found in Fig. 5. Although the shapes of the lines are almost the same, the resolution of the germanium detector using the X-Cooler II is obviously better than that using the LN_2 case.

The detailed information of totally eighteen characteristic peaks is collected in Table 1, where presented are the measured energy of characteristic line, the full width at half maximum (FWHM) and the full width at one-fifth maximum (FW[1/5]M) of each peak, and the ratio of two kinds of resolutions, which is defined as follows:

$$R = \frac{\text{resolution of } LN_2 - \text{resolution of X-Cooler II}}{\text{resolution of X-Cooler II}} \quad .$$

The maximum relative difference of measured energy of characteristic line for two cryogenic systems is at the level of one per mille, while the resolutions under X-Cooler

Table 1: Detailed information for each line of ^{152}Eu nuclide under different cooling condition.

Nomial lines (keV)	Liqudi nitrogen (keV)			X-Cooler II (keV)			R FWHM	R FW[1/5]M
	energy	FWHM	FW[1/5]M	energy	FWHM	FW[1/5]M		
121.8	121.67	1.23	2.35	121.69	1.10	1.99	1.10	1.18
244.7	244.18	1.36	2.41	244.36	1.23	2.10	1.11	1.15
344.3	343.63	1.47	2.57	343.92	1.32	2.26	1.11	1.14
411.1	410.51	1.55	2.67	410.84	1.43	2.42	1.08	1.10
444.0	443.28	1.61	2.72	443.69	1.42	2.37	1.13	1.15
488.7	488.01	1.60	2.70	488.45	1.46	2.47	1.10	1.09
586.3	585.48	1.67	2.79	586.05	1.56	2.57	1.07	1.09
678.6	677.68	1.72	2.76	678.38	1.54	2.56	1.08	1.08
688.7	687.71	1.75	2.90	688.45	1.63	2.61	1.07	1.11
778.9	777.77	1.84	2.97	778.61	1.70	2.73	1.08	1.09
867.4	866.13	1.94	3.19	867.05	1.80	2.91	1.08	1.10
964.0	962.72	1.99	3.20	963.78	1.87	3.01	1.06	1.06
1005.1	1003.83	2.02	3.25	1004.95	1.93	3.03	1.05	1.07
1085.8	1084.40	1.99	3.14	1085.58	1.87	2.93	1.06	1.07
1112.1	1110.62	2.10	3.42	1111.85	1.97	3.16	1.07	1.08
1212.9	1211.36	2.21	3.61	1212.71	2.04	3.33	1.08	1.08
1299.1	1297.41	2.27	3.67	1298.88	2.13	3.46	1.07	1.06
1408.0	1406.12	2.38	3.92	1407.71	2.22	3.61	1.07	1.09

II cooling is generally 10% better than those under LN_2 cooling (refer to the last two columns of Table 1). These experimental results celebrate the electric cooling system as an excellent replacement for liquid cooling system.

4 Conclusion

The liquid nitrogen cooling system has served BEMS for more than three years and kept the smooth commissioning of HPGe detector under the stable status. The obvious demerit of this cooling system lies in the occupation of some fraction of running time for the regular refilling.

The promising superseder of liquid nitrogen cooler is the mechanical cooler, i.e. the X-Cooler II that can provide the continuous cooling, and the regular interruption of data taking will be exterminated for good. At the same time, the safety hazards related to liquid nitrogen filling is eliminated as well. Furthermore, The laboratory measurements indicate that the resolution of HPGe detector under the X-Cooler II is even better than that of liquid nitrogen cooler, which is another favorable feature for BEMS.

The only thing needs the further experiment confirmation is the environment effect on the X-Cooler II cooling system, since the conditions under storage ring tunnel is rather different from those of laboratory. More relevant studies are planed for the new running year.

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